American Mineralogist, Volume 62, pages 374–376, 1977

Wide-range density separation of mineral particles in a single fluid system

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Abstract

A number of experiments were carried out with a Ferrofluid Density Separator to determine the practicality of separating micrometer-size particles into density fractions. The separators are normally used on much coarser material. The experimentation demonstrated that density separations of nonmagnetic particles as small as 50 micrometers (μm) were effective and reproducible and that the separator was easily operable far above the density of conventional liquid separation systems. Separations with smaller particle sizes were sometimes successful, but they could not be consistently reproduced.

Introduction

A device designed and described by Kaiser as a "Ferrofluid Density Separator" develops an apparent fluid density from nominally 1 to 20 g/cm^3 dependent on the magnitude of an imposed magnetic field gradient. The ferrofluid retains other normal properties of a liquid. Descriptions of ferrofluid devices, principles of operation, and some applications have been published (Kaiser and Miskolczy, 1970; Rosenweig, 1970; Moskowitz, 1974).

A number of experiments were carried out with a separator to determine the practicality of separating micrometer-size particles into density fractions. A shaped pole-piece electromagnet was used to generate a constant field gradient of about 1000 oersted per centimeter. The magnet is water-cooled and is operated with a continuously variable power supply up to about 250 amps. The volume applicable to sample processing is 50 cm^3. There are larger devices.

A typical ferrofluid is a stable suspension of submicrometer magnetite particles in kerosene. Three ferrofluids with differing magnetite concentrations were used, covering an apparent density range of 2 to 15 g/cm^3 when coupled with the magnet described. The three ferrofluids, with physical densities of 0.81, 0.86, and 0.95 g/cm^3, were prepared by AVCO Corporation, Systems Division, Lowell, Massachusetts.

A lucite sample cell was built to fit the magnet gap and contain the ferrofluid and sample. A central sliding valve in the cell isolates sink and float portions of separated samples. By varying the magnetic field gradient applied to a ferrofluid, it is possible to selectively sink or float a nonmagnetic solid object contained in the ferrofluid.

The ferrofluid force, F_m, on the object tends to move the object to the position of minimum field. When the field is aligned with the gravitational force, F_g, there is a point of equilibrium of the two forces such that (Kaiser and Miskolczy, 1970),

$$F_g = (\rho_s - \rho_l)g = M\Delta H/4\pi = F_m$$

Here ρ_s is the density of the solid, ρ_l is the density of the liquid or fluid, g is the gravitational force, M is the magnetization of the ferrofluid and ΔH is the magnetic field gradient. Increasing or decreasing ΔH (by changing the magnet current) from the equilibrium condition will cause the solid to float or sink respectively. A more detailed description of principle is given by Rosenweig (1970).

Experimental

The experimental work involved a procedure for processing particle samples, and determining the effect of particle size, ferrofluid concentration, and sample concentration on separation efficiency. The technique was tested with synthetic and natural particle mixtures.

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Table 1. Floating glass spheres

Test number	Sphere size (μm)	Separation results* % Float	% Sink
101	45-75	95	5
119	25-35	90	10
120	15-25	90	10
123	10-15	85	15
125	10-15	∿95	5
124	3-8	∿95	5

**Conditions of these tests were expected to float all of the glass spheres. Conditions were: Ferrofluid physical density 0.86 and at an apparent density of 4.8* g/cm^3*; separation time, one hour, except test 124 which was three hours; and sphere concentration was below 0.00001* cm^3 *per* cm^3 *of ferrofluid.*

Procedure

The sample is placed in the separation cell and the appropriate ferrofluid is added. The particles are dispersed by ultrasonic or mechanical mixing immediately before applying the magnetic field gradient. The cell remains in the magnetic separator for up to three hours. The sliding valve in the separation cell is inserted at the end of the magnetic separation period to divide the float and sink fractions. Each fraction is removed individually from the separation cell, filtered through a membrane filter and washed with heptane to remove the ferrofluid from the sample particles.

Ferrofluid concentration and sample concentration

Since the concentration-series of ferrofluids had overlapping separation ranges, tests were made to compare separation results with ferrofluids of different magnetite concentrations.

Ferrofluid with physical density 0.81 produced better separations than the ferrofluid with physical density 0.86 in all tests at the same separation apparent density. Experiments were conducted to determine the effect of sample concentration in the ferrofluid. Sample concentration was varied from nominally 0.001 to 0.01 cm^3 of sample per cm^3 ferrofluid with the sample materials quartz sand (<125 μm) and stainless steel spheres (24–48 μm). The lower sample concentrations yielded superior separations in all comparison tests. These comparisons were made by qualitative observation tests. The quantitative separation results in Tables 1–4 were carried out at lower concentrations in order to facilitate counting of particles in the float and sink fractions.

Table 2. Floating stainless steel spheres

Test number	Sphere size (μm)	Separation results* % Float	% Sink
90	50-60	99	1
91	50-60	96	4
93	50-60	96	4
88	24-48	14	86
94	24-48	36	64
95	24-48	29	71
96	24-48	24	76
126	12-20	50	50
127	6-12	25	75

**Conditions for these tests were expected to float all of the stainless steel spheres. Conditions were: Ferrofluid physical density 0.95 and at an apparent density of 11.5* g/cm^3*; separation time, one hour; and sphere concentration was below 0.00001* cm^3 *per* cm^3 *of ferrofluid.*

Table 3. Separation of stainless steel (s/s) and glass spheres

Test number	Sphere size (μm)	Sphere material	Separation results* % Float	% Sink
103	45-75	Glass	95	
	50-65	s/s		99
106	25-35	Glass	85	
	24-48	s/s		70
110	25-35	Glass	70	
	24-48	s/s		95
111	15-25	Glass	70	
	12-20	s/s		90
112	10-15	Glass	70	
	6-12	s/s		85
117	3-8	Glass	No separation	
	6-12	s/s		

**Conditions for these tests were expected to float all of the glass spheres and sink all of the stainless steel spheres. Conditions were: Ferrofluid physical density 0.86 and at an apparent density of 4.8* g/cm^3*; separation time one hour except test 117 which was three hours; and sphere concentration was kept below 0.00001* cm^3 *per* cm^3 *of ferrofluid.*

Table 4. Separation of garnet sand

Test number	Particle size (μm)		Separation results* % Float	% Sink
A	500-850	lights	98	
	500-850	garnets		100
B	250-500	lights	98	
	250-500	garnets		100
C	125-250	lights	98	
	125-250	garnets		100

**Conditions for these tests were expected to float the quartz, feldspars and muscovite (lights) and sink the garnets. Conditions were: Ferrofluid physical density 0.81 at an apparent density of 3.4* g/cm^3*; separation time, 15 minutes; and sample concentration below 0.001* cm^3 *per* cm^3 *of ferrofluid.*

Standard particles

Two series of experiments with a single kind of particle were carried out. Commercial glass spheres in various size ranges were processed under conditions expected to float the spheres. The results are shown in Table 1. In a separation time of an hour, about 90 percent of the spheres in all size ranges were floated. In a second series of experiments, commercial stainless steel spheres were floated. In these tests only particles above 50 μm were successfully floated, as shown in Table 2.

A series of experiments with mixed glass and stainless steel spheres was conducted under conditions expected to float the glass and leave the stainless steel in the sink fraction. The results of these tests are shown in Table 3. The separations were 70 to 95 percent efficient above 10 μm, but again the nearly quantitative results occurred when the particles were 50 μm and larger. The estimates of separation efficiencies were made by counting particles with a stereomicroscope.

Garnet sand

A sample of garnet sand was selected to demonstrate separation of minerals. Garnets have a density of about 4 g/cm^3 and are easily recognized under the microscope. The sample consisted of approximately 10 percent garnet plus quartz, feldspar, and muscovite. The magnetic particles were removed, and the sample was screened into fractions 125–250 μm, 250–500 μm, and 500–850 μm prior to the density separation. The sand was processed under conditions expected to float all but the garnets. No garnet was found in the light fraction, and about 2 percent of the light material was found with the garnet heavy fraction. The results are shown in Table 4.

Results

The experimentation demonstrated that density separation of particle groups with a ferrofluid separator is practical for particles as small as 50 μm. The processing is easily handled at densities much above conventional density separation systems.

Certain conditions lead to improved separations. Mechanical stirring or ultrasonic mixing of sample and ferrofluid improves separations. The lowest concentration (in magnetite) ferrofluid that will produce a desired separation should be used. The lowest sample concentration practical in a given situation should be used.

Particles in the millimeter size range can be separated if $\Delta\rho$ is 0.1–0.2 of a density unit. The $\Delta\rho$ must be increased as particle size decreases, in order to achieve effective separations. A $\Delta\rho$ of 0.5–0.75 density unit is estimated to be necessary for separations of particles as small as 50 μm.

Acknowledgment

This paper is based on work performed under Energy Research and Development Administration Contract E(45-1):1830.

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Manuscript received, March 4, 1976; accepted for publication, July 19, 1976.